

Research News — Observation of Exotic Heavy Baryons

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Abstract

We review the recent discoveries of exotic heavy baryons at the Fermi National Accelerator Laboratory.

According to a Press Release dated June 13, 2007 from the Fermi National Accelerator Laboratory (Fermilab), the D0 Collaboration has discovered a ‘triple-scoop’ exotic heavy baryon, which has been named Ξ_b^- (pronounced as ‘Zigh b’) with mass of about $5.774 \pm 0.019 \text{ GeV}/c^2$. The Collaboration has now posted its results on the internet, see [1]. Shortly afterwards, on June 15, the CDF Collaboration also at Fermilab announced its discovery of the same particle, with a mass $5.793 \pm 0.003 \text{ GeV}/c^2$ (see Fermilab Press Release dated June 25, 2007). This is the first instance of production of a baryon with three distinct ‘flavours’, *i.e.* with a quark from each of the three generations, and represents a landmark in the history of elementary particle physics. The three generations consist of u(up) and d(down), c(charm) and s(strange), t(top) and b(bottom) quarks and each of the quarks carries an intrinsic angular momentum or ‘spin’ of $1/2$ in units of \hbar ($\hbar = h/2\pi$, where h is the Planck’s universal constant). The Ξ_b^- is made up of d, s and b quarks. It should be noted here that the first generation is made up of the lightest of the quarks, and is the primary constituent of all stable matter. Somewhat earlier, another particle containing a single b-quark and two light quarks, the Σ_b was discovered by the CDF Collaboration in Fermilab in 2006 [2]. This highly unstable particle rapidly decays through the strong interactions with the emission of a pion and a Λ_b .

These discoveries are triumph for Quantum Chromodynamics (QCD), the presently accepted theory of strong interactions whose earliest form was announced by Murray Gell-Mann in Bangalore some 50 years ago, for a historical discussion see ref [3]. Although it was not very certain what quarks meant at that time, we now know that they are the microscopic degrees of freedom, along with gluons of the strong interactions, which are confined within strongly interacting matter (hadrons) which come in two varieties *viz.* baryons and mesons. The conventional protons and neutrons are examples of baryons while pions, which supply the internucleon force, are examples of mesons. The former are

made up of three quarks, while the latter are made up of a quark and an anti-quark pair. We now know that quarks come in six flavours, of which all but the u- quark are unstable due to the presence of the weak interaction. The latter is responsible for the decay of a free neutron, and is the only force that allows for the change in particle type. At the time Gell-Mann proposed his hypothesis, it was necessary to consider only three types, which are now called u, d and s quarks, carrying charges of $2e/3$, $-e/3$ and $-e/3$ respectively, where e is the proton charge. Both the s- and d- quarks can decay into a u- quark along with the emission of an electron and its anti-neutrino, while the s- quark can also decay into a u- quark and a muon and its anti-neutrino, where a muon is an elementary particle that is like an electron except that it is about 210 times heavier. The muon and electron are charged leptons, recalling that leptons are those particles that do not ‘feel’ the strong interactions, while neutrinos are what are called neutral leptons. Today we know that there is yet another more massive counterpart of the d- and s- quarks known as the b- quark. Correspondingly, there are cousins of the u- quark known as c- and t- quarks. Correspondingly, therefore, the b- quark can decay into both c- and u- quarks as it is heavier than each of them, and the c-quark can decay into s- and d- quarks for the same reason. This information will be of relevance in the latter part of this article.

Recalling that baryons are made up of quarks, one may readily see that the lightest baryons, the proton and neutron are made up of uud and udd quark combinations respectively. If one of the quarks in the proton or neutron is replaced by s quark in high energy physics experiments, where s quark and anti-quark pairs are produced in collisions and the former is captured by, e.g., the proton with the ejection of u or d quark, then one produces particles which have been named Σ , e.g., $\Sigma^+(\text{uus})$, $\Sigma^0(\text{uds})$, $\Sigma^-(\text{dds})$ while if the proton exchanges two of its intrinsic quarks for two s- quarks then one produces particles which are named Ξ , e.g., $\Xi^0(\text{uss})$, $\Xi^-(\text{dss})$. The results being reviewed in this article concern those experiments in which, for the first time baryons have been found with ‘s’ as well as a ‘b’ quark. While existence of such particles may be considered a very natural state of affairs in quark model of hadrons, their discovery actually proves to be a triumph of modern experimental particle physics.

Turning now to the specific discovery of the Ξ_b^- , these have been produced in highly energetic collisions of protons and anti-protons at the Fermilab Tevatron collider. In the fireball ensuing in these collisions there is a probability of producing many exotic states; the probability of production of the states Ξ_b in question is typically small as the b- quark produced in such a fireball must be able to pick up an s- quark in addition, and finally a light quark to form the baryon of interest. Then comes the question of identifying the production of such particles through their decay chains such as shown in Fig 1. In this case, the b- quark in the Ξ_b^- decays through the production of a virtual W^- which is the messenger of weak force, and a c- quark. The virtual W^- so produced then decays into an s- quark and a c- type anti-quark. The resulting $c\bar{c}$ then forms a bound state known as the J/Ψ , and leaves a distinctive signature through its decay into a $\mu^+\mu^-$ pair, while the s- quark produced in the W^- decay picks up the spectator d- and s- quarks in the mother Ξ_b^- particle to form the well-known

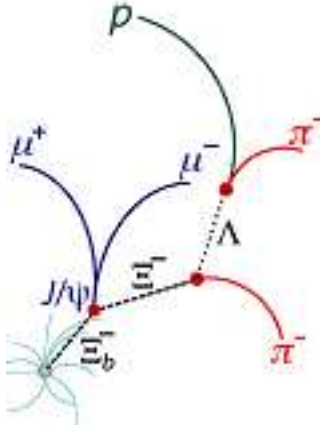


Figure 1: The figure shows the decay tree of new particle Ξ_b^- , see [1].

Ξ^- . This latter then decays when one of the s- quarks within it decays into Λ and π^- , and then the Λ in turn decays into a proton and a pion. This sequence of decays lends the name ‘cascade’ to this class of particles. The total decay can be written as, $\Xi_b^- \rightarrow J/\Psi \Xi^-$, with $J/\Psi \rightarrow \mu^+ \mu^-$, and $\Xi^- \rightarrow \Lambda \pi^- \rightarrow p \pi^- \pi^-$. The D0 collaboration observed 19 candidate events for the production of these particles. Based on its own search strategy, the CDF collaboration reported 17 candidate events. The mass determinations are in agreement with the theoretical predictions based on heavy baryon chiral perturbation theory, the effective low energy theory of the strong interactions in this sector, which predicts its mass to be $5.806 \pm 0.008 \text{ GeV}/c^2$ [4]. Note here that while this particle has spin 1/2 which may be obtained from the three constituent quarks each of which carries spin of 1/2, the theory also predicts a spin 3/2 counterpart that would be denoted by Ξ_b^{*-} , which is yet to be observed. It may be noted that the D0 results come from 1.3 fb^{-1} (fb^{-1} stands for ‘inverse femtobarn’, a standard unit for luminosity) integrated luminosity, while the CDF results come from 1.9 fb^{-1} integrated luminosity. Earlier experiments at LEP collider at CERN had also reported an indirect evidence of Ξ_b^- baryon based on excess of same sign $\Xi^- l^-$ events in jets [5, 6].

Not so long ago, according to a Fermilab’s Press Release dated October 23, 2006, the CDF Collaboration discovered the particles denoted by Σ_b^+ made of b and two u quarks, and also Σ_b^- made of b and two d quarks. Both of these particles carry a spin of 1/2. The CDF Collaboration also discovered their spin 3/2 counterparts denoted by Σ_b^{*+} and Σ_b^{*-} . CDF results came from integrated luminosity of 1.1 fb^{-1} . These particles have been detected through their sequence of decays; $\Sigma_b^{\pm} \rightarrow \Lambda_b^0 \pi^{\pm}$ with $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$, $\Lambda_c^+ \rightarrow p K^- \pi^+$.

The observed masses are [2]

$$\begin{aligned} m_{\Sigma_b^+} &= 5807.8 \pm 2.0 \pm 1.7 \text{ MeV}/c^2, & m_{\Sigma_b^{*+}} &= 5829.0 \pm 1.8 \pm 1.8 \text{ MeV}/c^2, \\ m_{\Sigma_b^-} &= 5815.2 \pm 1.0 \pm 1.7 \text{ MeV}/c^2, & m_{\Sigma_b^{*-}} &= 5836.4 \pm 2.0 \pm 1.8 \text{ MeV}/c^2. \end{aligned}$$

As expected, the spin 3/2 counterparts are more massive due to the contributions from the magnetic energy costs for aligning the spins of the three quarks to produce this state, in comparison with the energy costs for the spin 1/2 states. The corresponding predictions from various theories are in agreement with the experimentally observed masses.

In summary, noting that there has been significant progress in understanding b baryons theoretically, up until the discoveries reviewed here, none but Λ_b^0 had been observed experimentally. This particle was already observed in the early 1980's, for a discussion see ref. [7]. These heavy baryons provide a testing ground for various approaches to the non-perturbative regime of QCD. Since Ξ_b^- has all distinct quarks, it could help in understanding how individual quarks are bound together inside hadrons. With the discoveries reviewed here, a new era of precision measurements of their properties is now on the horizon.

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